



RESEARCH MEMORANDUM

EFFECTIVE THERMAL CONDUCTIVITIES OF MAGNESIUM OXIDE

STAINLESS STEEL, AND URANIUM OXIDE POWDERS

IN VARIOUS GASES

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

As a part of a general investigation of the effective thermal conductivities of powders, tests were conducted to determine the conductivity of magnesium oxide, stainless steel, and uranium oxide powders in various gases at temperatures between 120° and 1455° F. Fair agreement was obtained between conductivities calculated from experimental data for fine magnesium oxide and stainless steel powders and those calculated from a simplified analysis from a previous investigation, although the experimental values are somewhat higher. Runs were also made to determine the effect of gas pressure on effective thermal conductivity.

INTRODUCTION

In reference 1, an analysis was made to predict the effective thermal conductivity of a powder from the properties of the solid and gas which make up the powder. The results of an investigation to determine the thermal conductivity of magnesium oxide powder in various gases and the results of previous experimental investigations agreed closely with the predicted values.

As a further check on the analysis, and to obtain data for powders of current technical interest, tests were conducted at the NACA Lewis laboratory to determine the thermal conductivity of finer magnesium oxide than was used in reference 1, as well as stainless steel and uranium oxide powders in various gases. The test sections containing magnesium oxide and uranium oxide were filled by the General Electric Company.

EXPERIMENTAL INVESTIGATION

Apparatus

The apparatus used in this investigation is the same as that described in reference 1 with the exception of minor alterations to the design of the test section and its enclosing gas chamber, which are described in the following sections.

Test section. - The test section consisted of two concentric tubes separated by the powder being tested. The inner tube was heated electrically and the outer tube cooled by convection. Temperatures were measured by thermocouples placed at various radial positions in the powder. The test section is the same as that fully described in reference 1, with the following exceptions: The central porcelain with the wound heating elements and the thermocouples stretched through the powder to obtain radial temperature measurements were held in position by poured ceramic end plugs instead of machined ceramic disks. A 1/4-inch-diameter tube for adding the powder, and the heater leads to the power sources, were also brought out through the end plugs.

In the test section containing magnesium oxide powder, four groups (90° apart) of five radially positioned thermocouple wire junctions were located in approximately equal increments in a plane across the center of the test section. The thermocouple wires stretched through the test section containing stainless steel powder were coated with an insulating cement to electrically insulate the thermocouples from the stainless steel powder. Because the added cement coating displaced a considerable portion of the usable powder volume, four groups of four, instead of five, radially positioned junctions were located in approximately equal increments across the center plane. The same test section was used to obtain data with uranium oxide powder.

The power leads brought out through the powder and through the ceramic end plugs were also cement-coated to eliminate short circuiting through the powder. As a further precaution, the inner surface of the stainless steel tube containing the powder was also coated with insulating cement.

In the test section containing uranium oxide powder, a carbon-rod heating element was substituted for the wound Nichrome wire main element in order to obtain data at high temperatures where the main Nichrome heater proved to be inadequate. The 1/4-inch-diameter carbon rod was inserted through the hollow ceramic tube core of the test section with electrical terminal blocks located at each end outside the test section ends. The Nichrome end heaters were used in conjunction with the carbon rod.

Gas chamber. - Thermocouple and power leads were brought out from the ends of the test section through the gas chamber walls by means of fittings employing the crushing action of soapstone cones around the wires to effect a high-pressure seal. Each end of the gas chamber was sealed with the use of a rubber O-ring between the chamber end and its flange. By means of suitable tube connections to a hole drilled in each flange of the gas chamber, the test section could be evacuated by the use of a vacuum pump at the outlet end or supplied with purified and dried bottled air, helium, or argon at the inlet end.

Procedure

The test sections were filled through the filler tubes with magnesium oxide, type 446 stainless steel containing 27 percent chromium, and uranium oxide powders giving fractional volumes occupied by the solid particles of 0.64, 0.53, and 0.63, respectively. The particle sizes of the powders are given in table I.

The distances between the junction of the thermocouple wires stretched through the powder and their positions relative to the outer container wall and main heating element were obtained from X-ray photographs taken of the test section after it was filled in the case for magnesium oxide. For the stainless steel and uranium oxide powders, the X-ray photographs were taken before filling because of the interference of these powders with the X-ray photographing of the thermocouples.

Data were obtained for air, helium, and argon gases over a range of average powder temperatures and pressures given in the following table:

Powder	Average powder temperature, °F	Pressure, lb/sq in. abs
Magnesium oxide	120-825	19-261
Stainless steel	154-678	14-264
Uranium oxide	135-1455	89-164

No data were obtained for uranium oxide powder in air because of the resulting chemical reactions at elevated temperatures.

The method of obtaining the data is presented in reference 1. In addition, runs were made at elevated temperatures with the carbon heating rod in the test specimen filled with uranium oxide. After low-temperature data had been obtained with the Nichrome wire heating element, and the carbon rod element had been installed, comparative runs were made of the low-temperature data. This was done in order to

compare the values of thermal conductivity obtained by using the carbon rod with those obtained by using the Nichrome heater. Only the portion of the power input to the carbon rod between the end-guard heaters was charged to the thermal conductivity determination of the powder. In all cases, good agreement with the low-temperature data was obtained. Data were then obtained at successively higher temperatures until failure of thermocouples rendered computation of values of thermal conductivity questionable.

Reduction of Experimental Data

The equations used in calculating values of thermal conductivity of the powder and gas mixtures from the experimental data are given in reference 1, including the correction for eccentricity of the inner tube with respect to the outer tube. Reference 1 gives also the thermal conductivities of solid magnesium oxide and of the various gases used in the tests.

Figure 1 shows the variation of thermal conductivity of solid chromium stainless steel with temperature as obtained from reference 2.

RESULTS AND DISCUSSION

Experimental Effective Conductivities

Experimental thermal conductivities of magnesium oxide, stainless steel, and uranium oxide powders in various gases are presented in figure 2. Inasmuch as the effective conductivity of a powder-gas mixture is affected by the gas pressure up to a certain pressure level, depending upon the gas, the temperature, and some characteristic dimension of the gas spaces, all the data presented were obtained at pressure levels of sufficient magnitude to result in no effect on the conductivity as discussed in a later section entitled "Effect of Pressure on Conductivity."

Thermal conductivities of magnesium oxide powder in argon, air, and helium gases for temperatures between 120° and 825° F are plotted in figure 2(a). The thermal conductivity of the powder increases with temperature for each gas in much the same manner as that of the coarser magnesium oxide powder presented in reference 1, except for helium where a maximum value is obtained at about 400° F. Inasmuch as all the data for helium were obtained after those for air and argon up to about 375° F and before those beyond 375° F, any error in experimental instrumentation would result in a discontinuity of the air and argon data, which is not in evidence in the curves.

In figure 2(b) the variation of thermal conductivity of stainless steel powder with temperature for a range of 150° to 680° F is presented; an increase with temperature is also obtained with the same gases. Inasmuch as the thermal conductivity of solid magnesium oxide decreases with temperature (ref. 1) whereas the values for solid stainless steel increase with temperature (fig. 1), the results indicate that the conductivity of the gas is more important than the conductivity of the solid in determining the conductivity of the powder since the conductivities of all the gases increase with temperature.

In figure 2(c) is plotted the variation of thermal conductivity of uranium oxide powder with temperature for a range of 135° to 1455° F in argon and helium. A slight increase in conductivity with temperature is obtained for argon, while for helium the conductivity is approximately constant with temperature change. At the present time, the variation of conductivity of solid uranium oxide with temperature has not been established. However, the slight variation of conductivity with temperature of the powder indicates that the conductivity of the solid probably decreases very rapidly with temperature inasmuch as the conductivity of argon and helium increases with temperature. As mentioned before, the gas phase is more important than the solid in determining the powder conductivity.

For all the powders, the conductivity in helium is much greater than in the other gases because of the much greater conductivity of helium.

Comparison of Analytical and Experimental Results

A simplified analysis was made in reference 1 to predict the effective thermal conductivities of a powder when the thermal conductivities of the solid k_s and the gas k_g and the fraction of space a occupied by the gas are known. The analysis indicated that the effective conductivity increases at an increasing rate as the fraction of space occupied by the gas decreases. The experimental results for coarse magnesium oxide powder in argon, air, and helium agreed well with the analysis.

In figures 3(a) and 3(b) are presented the comparison of the analysis with the experimental results for fine magnesium oxide and stainless steel powders in argon, air, and helium. The solid curve shown on each plot indicates the predicted effective thermal conductivity k for a powder and gas mixture corresponding to the fraction of space occupied by the gas, which was 0.36 and 0.47 for the magnesium oxide and stainless steel powders, respectively. For both powders with all the gases, the data fall to the right of the predicted line, the

deviation being about 15 percent for the magnesium oxide powder at both high and low temperatures and with all gases except air where the data fall progressively farther away from the line with temperature increase from 560° to 610° F. It is of interest to note that in reference 1 the data for coarse magnesium oxide and air followed the predicted line fairly well, while the data with helium deviated farther from the line with temperature increase. The data for stainless steel deviate about 15 percent at the lowest k_s/k_g of about 110 (corresponding to data with helium up to 678° F powder temperature), and about 35 percent at the highest k_s/k_g of about 1130 (corresponding to data with argon at about 200° F powder temperature). The data for air at intermediate values of k_s/kg deviate slightly less than for argon.

The much greater spread of the data along the ordinate k_s/k_g for the magnesium oxide powder than for the stainless steel powder with approximately the same temperature range for each gas is a result of the opposite variation of conductivity with temperature of the respective solids.

A photograph magnified 55.5 times of representative particles of the stainless steel powder used in the experiments is shown in figure 4(a). It can be seen that a greater number of the particles are spherical in shape than for the magnesium oxide powder shown in figure 4(b), and that the magnesium oxide powder consists of a large percentage of very small particles in contrast to the stainless steel powder as indicated in table I.

Inasmuch as the thermal conductivity variation with temperature for solid uranium oxide is not presently known, no comparison with the analysis for that powder-gas mixture has been made.

Effect of Pressure on Conductivity

The effect of gas pressure on the effective thermal conductivity of magnesium oxide and stainless steel powders is presented in figure 5.

In reference 1 it was shown that the effect of gas pressure on the effective thermal conductivity of a powder-gas mixture can be explained by the kinetic theory of gases wherein use of the Knudsen number (the ratio of mean free path of the gas molecules to a characteristic dimension of the gas spaces) enables prediction of the effect of gas pressure on the effective thermal conductivity. Inasmuch as the size of the gas spaces is of the same order of magnitude as the size of the particles, the characteristic dimension is taken as the weighted mean size of sieve required to retain the particles; from the data given in table I the dimensions are found to be 0.0001463, 0.000583, and

0.000286 feet for the magnesium oxide, stainless steel, and uranium oxide powders, respectively. From the Knudsen equation, the predicted pressure at which the conductivity begins to vary appreciably with pressure (breakaway pressure) is given by

$$p_b = 1770 \times 10^{-24} \frac{t}{s^2 l_s} \quad (1)$$

where

p_b breakaway pressure, lb/sq ft abs

t gas temperature, $^{\circ}$ R

s molecular diameter determined from viscosity, ft

l_s weighted mean sieve size required to retain particles, ft

The diameter $s = 6.23 \times 10^{-10}$ for helium, 9.9×10^{-10} for air, and 9.45×10^{-10} for argon. In reference 1, good agreement was found between predicted breakaway pressures and experimental data for coarse magnesium oxide powder. As a further check on the predicted values, experimental data were obtained for the fine magnesium oxide and stainless steel powders in helium, air, and argon at various temperatures. As can be seen in figure 5, good agreement was obtained between predicted values (indicated by solid vertical lines in figure) and experimental data. For the thermal conductivities presented in figure 3, the pressures were, in all cases, above those given by equation (1).

The data in the curve for helium in figure 5(b) were obtained at higher pressures in order to detect any effect of free convection on the effective thermal conductivity. From the curve it can be seen that, for the pressure range shown, free convection is not an important factor in determining the effective thermal conductivity. If there were appreciable free convection in the powder, the conductivity would continue to increase inasmuch as free convection is a function of the density of the gas.

SUMMARY OF RESULTS

The following results were obtained from an investigation of effective thermal conductivities of magnesium oxide, type 446 stainless steel containing 27 percent chromium, and uranium oxide powders:

1. Effective thermal conductivities increased with temperature except for the uranium oxide - helium mixture and magnesium

oxide - helium mixture, where no variation with temperature and a maximum value with temperature were obtained, respectively.

2. Fair agreement was obtained between conductivities calculated from experimental data for fine magnesium oxide and stainless steel powders and those calculated from a simplified analysis from a previous investigation, although the experimental values were somewhat higher.

3. Good agreement was obtained between calculated value of Knudsen number at which the conductivity begins to vary appreciably with pressure and the experimental data for magnesium oxide and stainless steel powder in helium, air, and argon.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 7, 1953

REFERENCES

1. Deissler, R. G., and Eian, C. S.: Investigation of Effective Thermal Conductivities of Powders. NACA RM E52C05, 1952.
2. Hogan, C. L., and Sawyer, R. B.: The Thermal Conductivity of Metals at High Temperature. Jour. Appl. Phys., vol. 23, no. 2, Feb. 1952, pp. 177-180.

TABLE I. - PARTICLE SIZE OF POWDERS

[Calculation of equivalent diameter of a representative number (100) of particles as determined by a microphotograph of the particles of type 446 stainless steel containing 27 percent chromium is 0.0070 inch. All powder in the test section passed through 60 mesh sieve but was retained on 100 mesh sieve.]

Mesh	Sieve opening a _{12S} , in.	Average amount of powder retained on sieve, a _{100 f} , percent	Line numbera, n
Magnesium oxide			
60	0.0098	0.0	1
80	.0070	.32	2
100	.0059	.54	3
150	.0041	4.85	4
200	.0029	12.73	5
270	.0021	21.83	6
325	.0017	14.93	7
Through 325	Assumed .0003937	44.60	8
Uranium oxide			
100	0.0059	0.0	1
150	.0041	66.0	2
Through 325	Assumed .0003937	34.0	3

aSee reference 1.

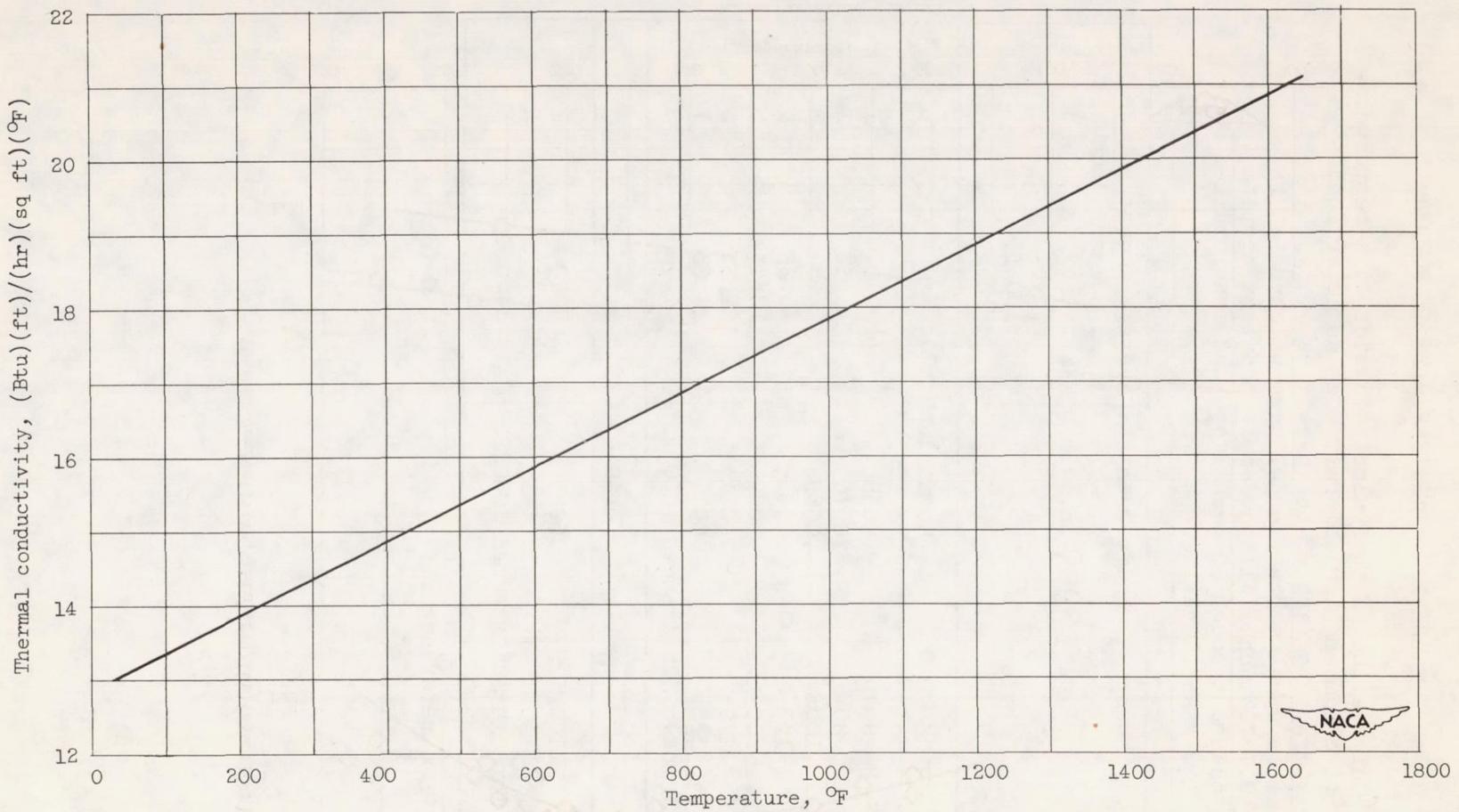
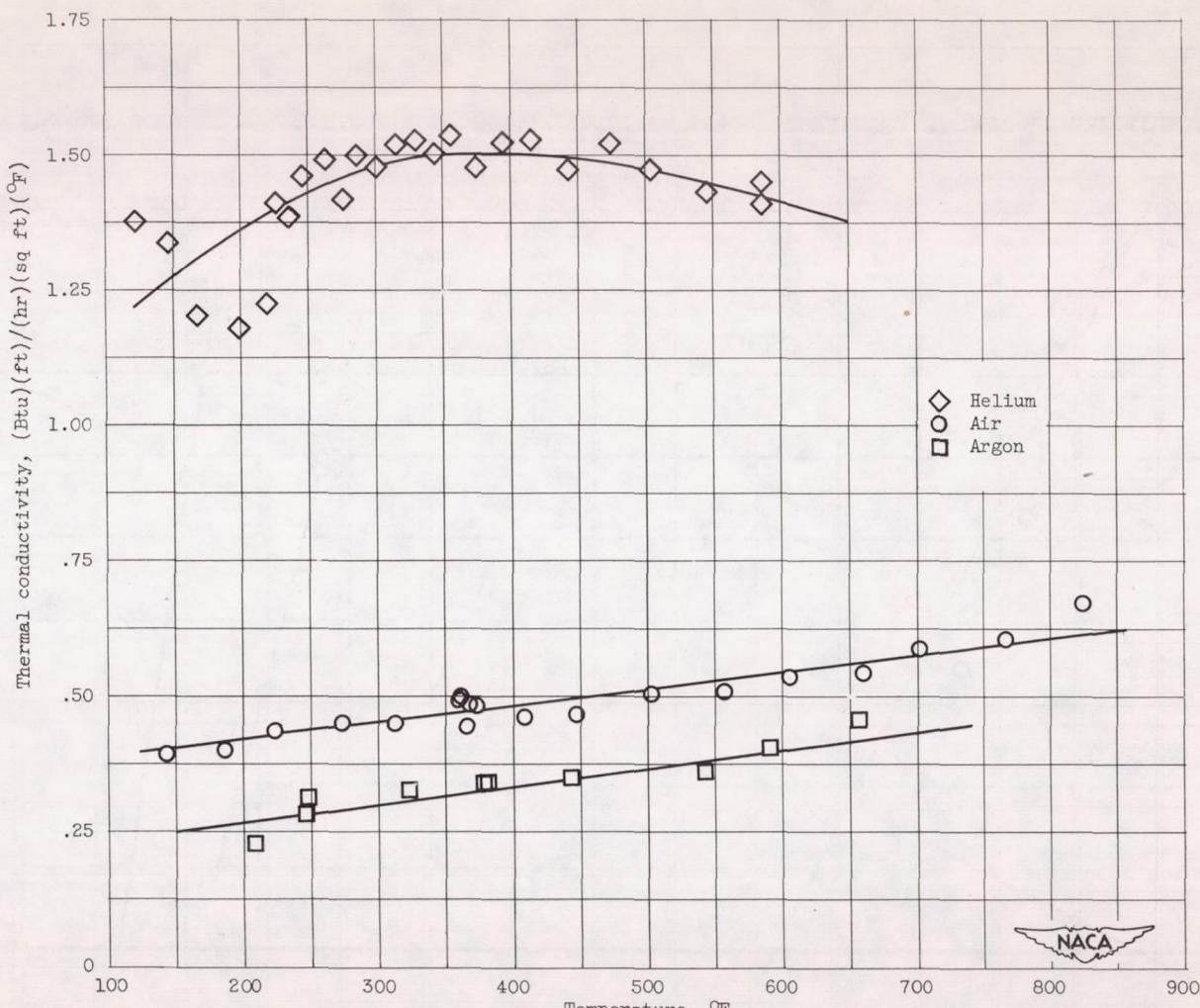
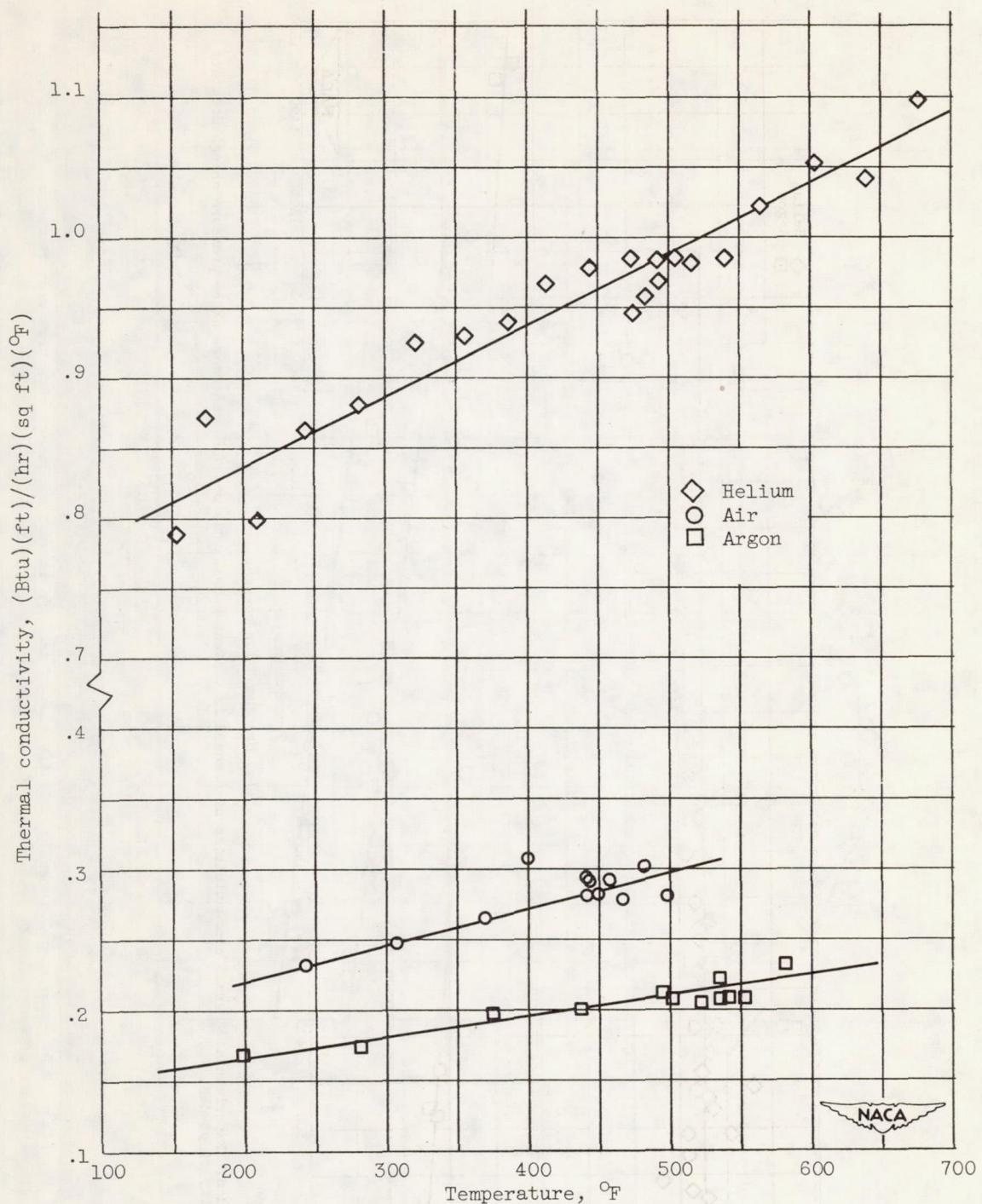


Figure 1. - Thermal conductivity of solid type 446 stainless steel containing 27 percent chromium (ref. 2).



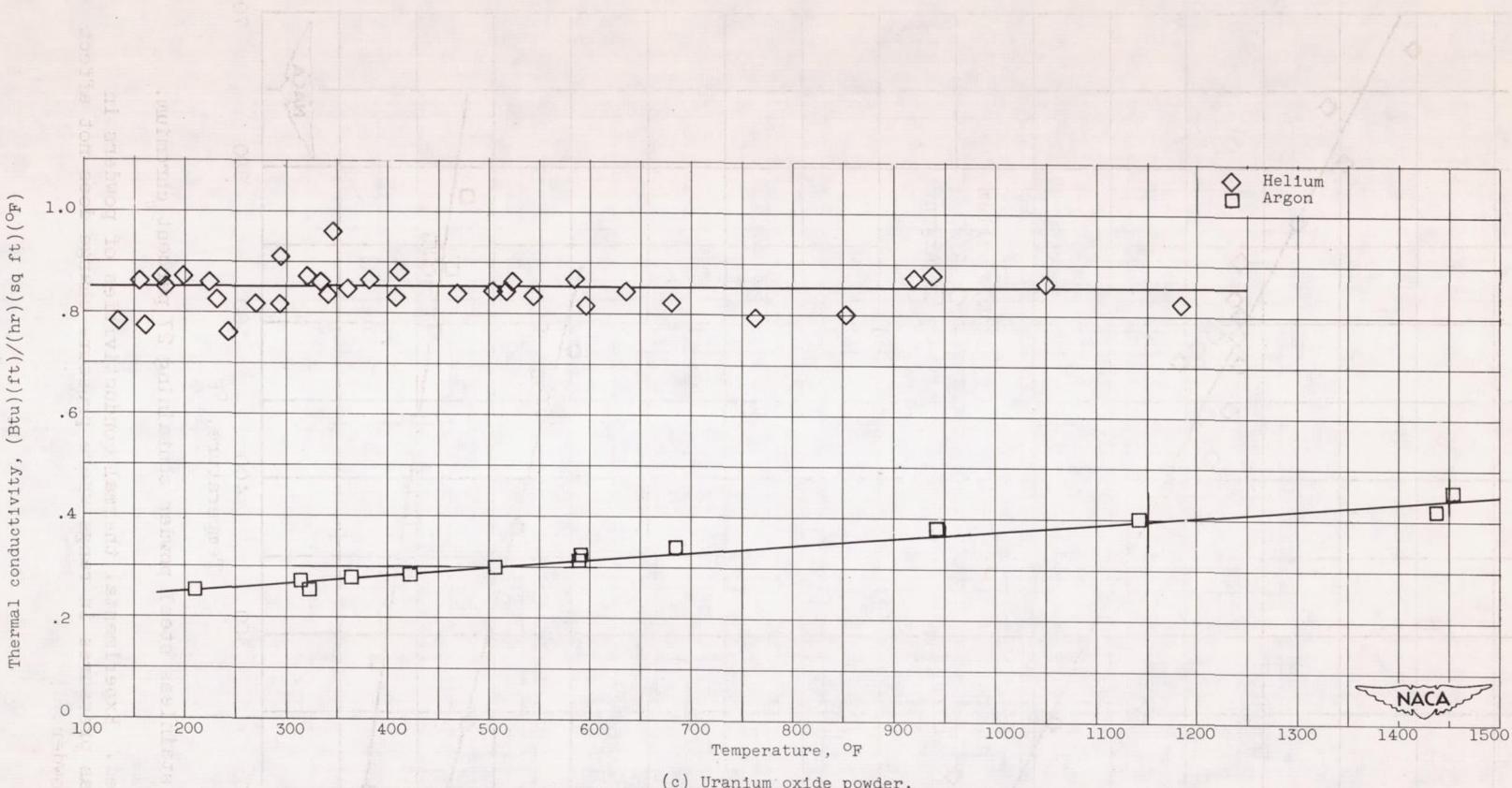
(a) Magnesium oxide powder.

Figure 2. - Experimental thermal conductivities of powders in various gases. *Gas pressures in range where pressure change does not affect conductivity of powder.



(b) Type 446 stainless steel powder containing 27 percent chromium.

Figure 2. - Continued. Experimental thermal conductivities of powders in various gases. Gas pressures in range where pressure change does not affect conductivity of powder.



(c) Uranium oxide powder.

Figure 2. - Concluded. Experimental thermal conductivities of powders in various gases. Gas pressures in range where pressure change does not affect conductivity of powder.

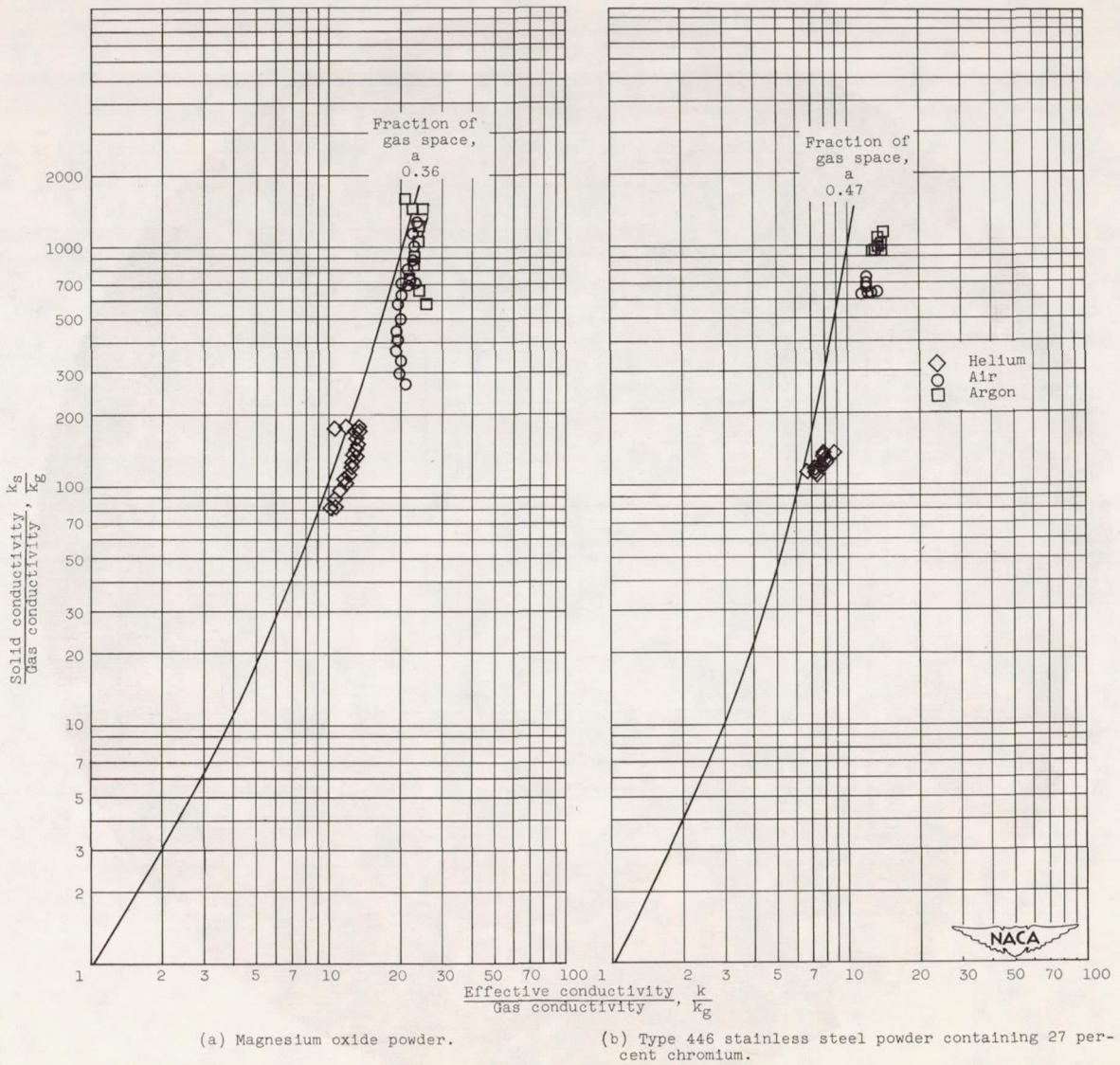


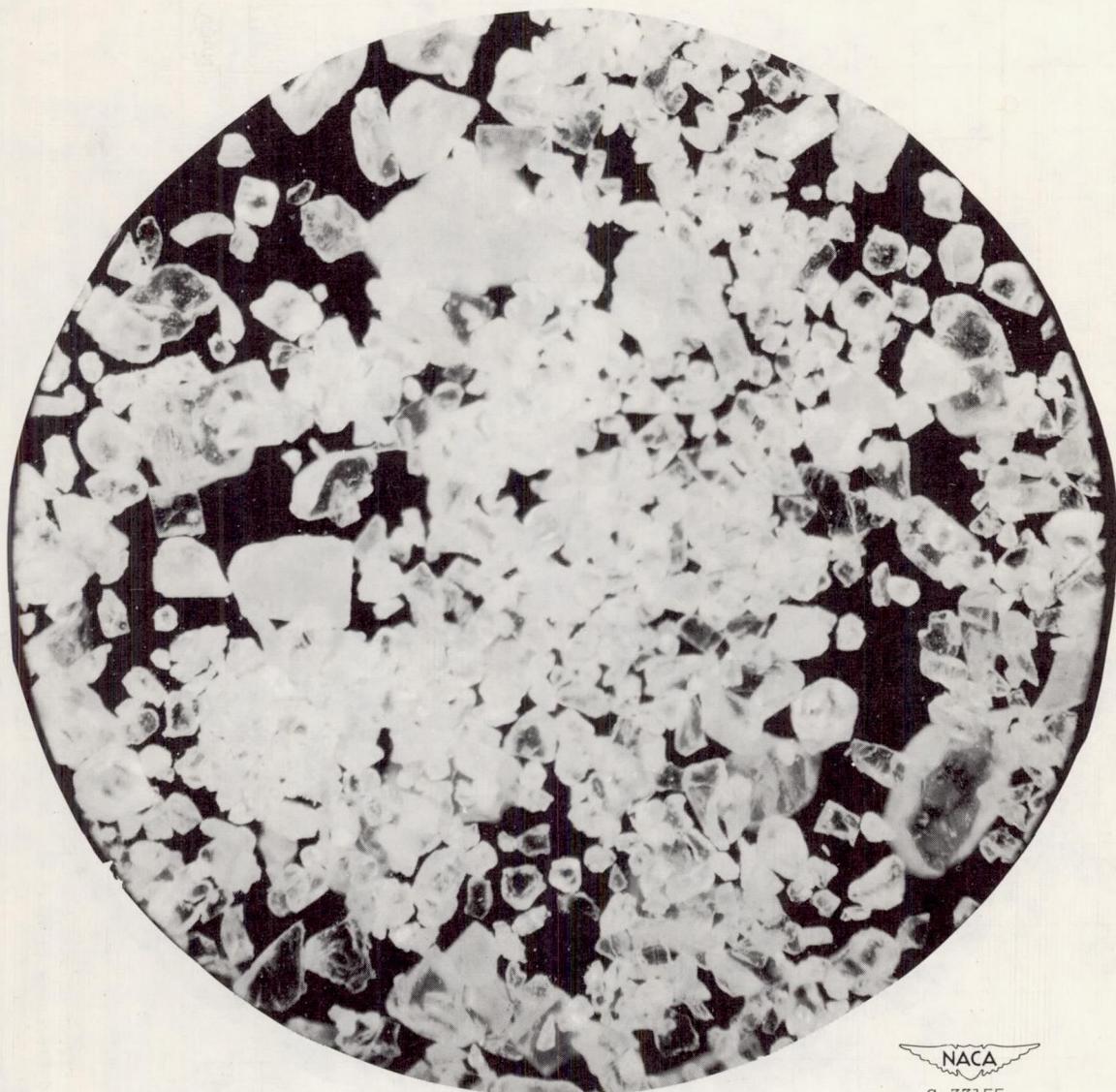
Figure 3. - Comparison of analytical with experimental results for magnesium oxide and stainless steel powders.



NACA
C-33154

(a) 446 Chromium stainless steel powder containing 27 percent chromium. Magnified 55.5 times.

Figure 4. - Enlarged photographs of powder particles.



NACA
C-33155

(b) Magnesium oxide powder. Magnified 55 times.

Figure 4. - Enlarged photographs of powder particles.

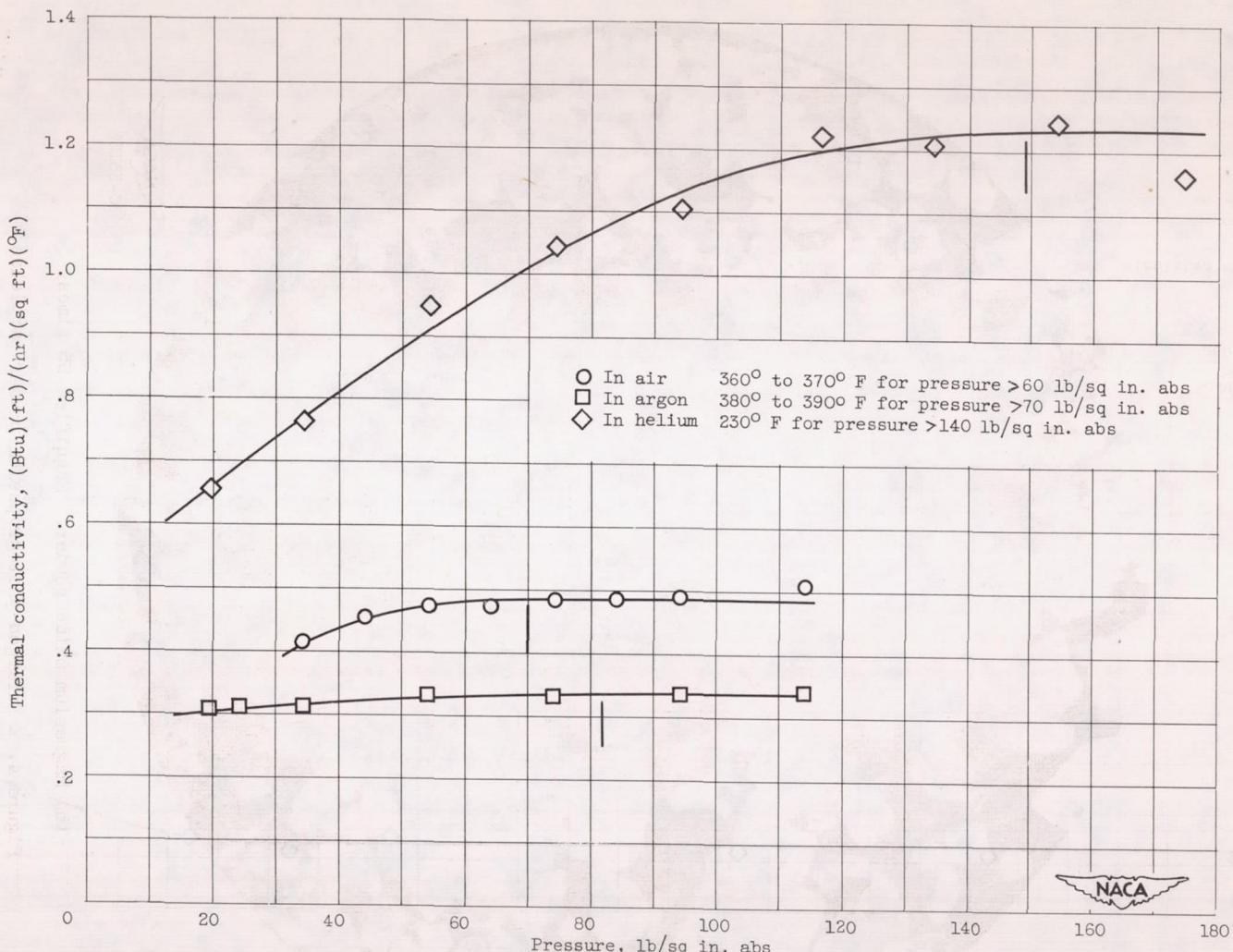
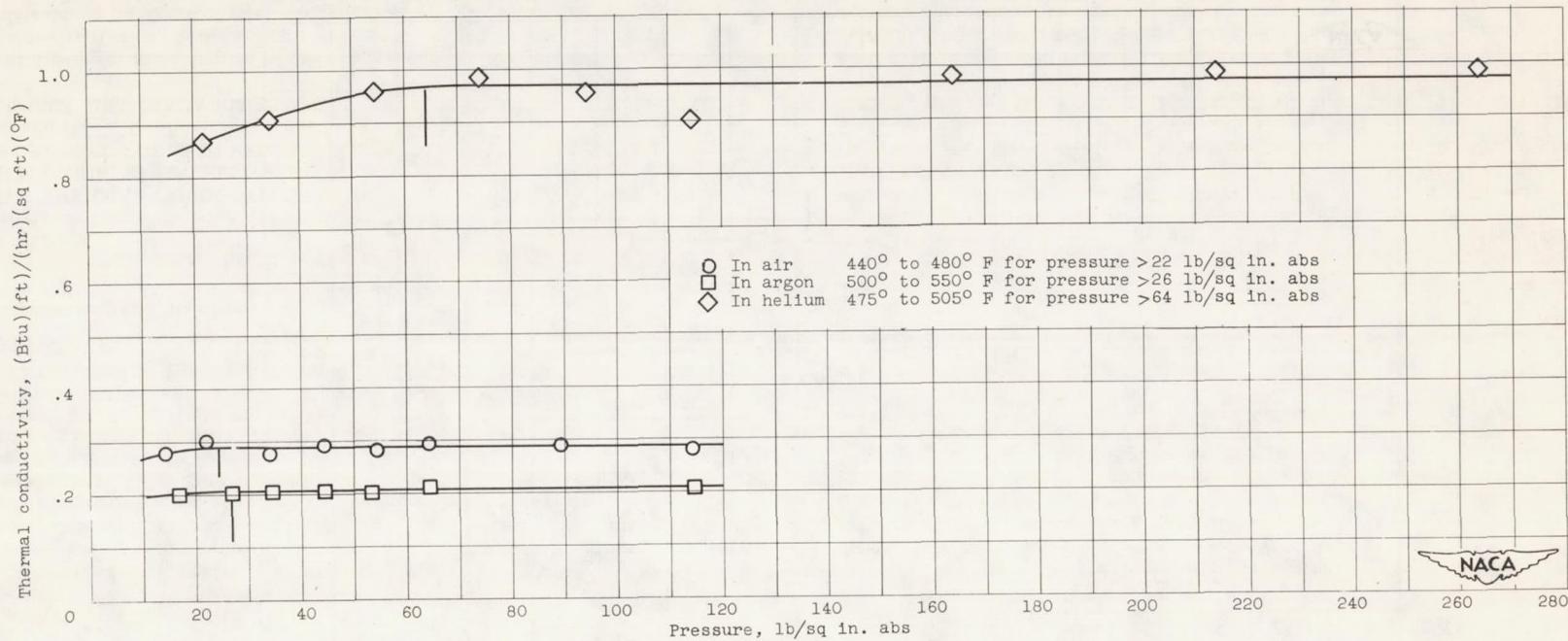


Figure 5. - Effect of gas pressure on thermal conductivity of powders in various gases. Vertical lines represent calculated breakaway pressures.



(b) Type 446 stainless steel powder containing 27 percent chromium.

Figure 5. - Concluded. Effect of gas pressure on thermal conductivity of powders in various gases. Vertical lines represent calculated breakaway pressures.